Energy Generation using Piezo Film (I)

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The following text was originally intended to form a brief summary of the energy generation capabilities of piezo film. As the company name has changed more than once since 1991, a brief history of the piezo film group is outlined below.

Division History:

1969: Kawai discovers high piezoelectric effect in PVDF.

1976: Pennwalt Corporation funds basic R&D activity in piezoelectric PVDF.

1982: Pennwalt establishes new Business Venture in Kynar® Piezo Film, based at King of Prussia, PA, later moving to Valley Forge, PA.

1984: Syrinx Innovations Ltd established in Edinburgh, UK as European sales office and development center - later renamed as Pennwalt Piezo Film Ltd.

1990: Elf Aquitaine acquires Pennwalt Corporation and forms Elf Atochem North America. Piezo Film group changes name to Atochem Sensors Inc (Atochem Sensors Ltd in UK).

1993: AMP Incorporated acquires Piezo Film Sensors Division from Elf Atochem. Piezo Film Division renamed AMP Sensors. European office moves to Stanmore, within headquarters of AMP of GB.

1995: AMP establishes Sensor Competency Center in Bensheim, Germany

1998: Measurement Specialties, Incorporated acquires Sensors Division from AMP Inc. Sensor Products Division remains at Valley Forge, PA, with European office near Frankfurt, Germany.

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Energy Generation using Piezo Film

Richard H Brown

1) Basic Principles

The fundamental piezoelectric coefficients for charge or voltage allow us to predict, for small stress levels, the charge density (charge per unit area) or voltage field (voltage per unit thickness) developed by the polymer.

1.1) Charge Mode

We can say that, under conditions approaching short-circuit:

$$D = Q/A = d_{3n}X_n \qquad (n = 1, 2, 3, h \text{ or } t)$$

where
- D = charge density generated
- Q = charge developed
- A = metallized electrode area
- d = appropriate piezoelectric coefficient
- X = stress applied in relevant direction

It is most important to note that although the d_{3n} coefficient is commonly expressed in pC/N, the more correct form would be $(pC/m^2)/(N/m^2)$ since the areas involved are very often different and cannot be "cancelled".

1.2) Voltage Mode

The open-circuit output voltage is given by:

$$V_0 = g_{3n}X_nt \qquad (n = 1, 2, 3, t \text{ or } h)$$

where g is the appropriate piezoelectric coefficient,
X is the applied stress in the relevant direction,
and t is the film thickness.

2) Energy Output

To predict the maximum energy output of the film, we need to know the maximum stress that can be applied. This can be difficult to evaluate accurately, since the time of application of stress has a strong bearing on the results. It has been found that the limits quoted in the Technical Manual may be exceeded under certain conditions, and that the precise figure for maximum compressive strength in particular is very elusive. In practice, it is generally more difficult to arrange destructive stress in the thickness direction, since the stressed area is usually high and so very high force is required to produce the stress.

In tension, the low cross-sectional area of the film allows the limit to be reached with comparatively low forces. In this mode, it is found that high stress levels cause an increase in the capacitance of the film. This dynamic capacitance effect consequently reduces the voltage measured under open-circuit conditions, and an actual reversal of characteristic may be encountered (progressively higher stress produces lower output voltage). The charge generation, however, appears to be nearly linear.

The following summary indicates true measured results from multiple trials using a standard element style (DT4-052K), and interpolated specific results, for various quantities:

Description: Piezo Element DT4-052K, active area 155.5 x 18.5 mm, thickness 52 µm, giving:

Active electrode area	:	$2.877 \times 10^{-3}\ m^2$
Static capacitance	:	5.86 nF
Cross-sectional area	:	$962 \times 10^{-9}\ m^2$
Active film volume	:	$149.6 \times 10^{-9}\ m^3$

2.1) Maximum charge observed	:	20 µC approx, giving 6.95 mC/m^2
2.2) Maximum voltage observed	:	1600 V, giving 30.8×10^6 V/m
2.3) Max dynamic capacitance	:	12.5 nF (from 2.1 & 2.2 above)
2.4) Max converted energy	:	30.9 mJ (53 V measured across 22 µF capacitor) giving 207 kJ/m^3

Notes:

The result 2.1 indicates a maximum applied stress without failure of about 350 MPa (in the stretch direction) when the observed charge is related back to stress. However, some non-linearity in the charge vs. stress curve is expected, so that the actual applied stress may well have exceeded this value.

Result 2.2 cannot be compared directly, because of the dynamic capacitance effect. If the capacitance was fixed at its initial unstressed value, we would have expected peak voltages around 3.4 kV for the same stress level.

Result 2.4 was obtained using a transformer, diode bridge and storage capacitor, all optimised for a given set of conditions. Note that the energy level predicted from results 2.1, 2.2 and 2.3 is only 16 mJ. The discrepency arises because the charge measurements, and the final converted (stored) energy, are measured under low-impedance conditions, while the voltage measurements are essentially open-circuit. The electrical conditions affect the mechanical behaviour of the film. If charge is not removed from the film, then the accumulating charge impedes further build-up, and a force acting against the applied force will be encountered.

3) Conclusions

3.1) Maximum one-shot stretch-direction stress is about 350 MPa

3.2) Maximum charge density expected is about 7 mC/m^2

3.3) Maximum converted energy density expected is about 200 kJ/m^3

3.4) Effective capacitance can be expected to double as limiting tensile stress is approached, thus greatly affecting open-circuit voltage measurements

3.5) Further experiments have suggested that operation at about 10% of the energy level above can be sustained for long periods with no degradation